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LONG-TERM CREEP ASSESSMENT OF CANDIDATE METALS FOR HIGH LEVEL NUCLEAR WASTE DISPOSAL CONTAINERS - INTERIM REPORT

Report No. 90-241-K

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ABSTRACT

Several alternative containers are being developed for disposal of used fuel bundles from CANDU nuclear power stations. The outer shell of the containers will be made of titanium or copper. One container design has steel cask supporting the outer shell. To prevent container failure, strain in the outer shell and the steel cask cannot exceed safety limits. As part of the long term assessment program for the container, 500-year creep is estimated in three metals (high-purity oxygen-free copper, commercially pure titanium and mild steel) at a temperature of about 125°C. Only limited data is available in literature for the three metals, at the operating conditions of the containers. Creep in steel and titanium could only be estimated by testing. Tests were conducted at Ontario Hydro Research Division. Creep in copper was approximated using the available literature results. Creep in steel is lower than in the other two metals. Creep starts when the stress reaches about 67% yield and increases quickly as the stress approaches yield. Creep strain in titanium is more pronounced and starts at about 50% yield. Creep in copper is high and should not be ignored at any stress level. The proposed creep rate formulations will be used for finite element analysis of a long term container performance. A method for simplified analysis of long term material creep is proposed.

job	file	date	report no.
21-150-461	825.123	December 3, 1990	90-241-K

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EXECUTIVE SUMMARY

LONG-TERM CREEP ASSESSMENT OF CANDIDATE METALS FOR HIGH LEVEL NUCLEAR WASTE DISPOSAL CONTAINERS - INTERIM REPORT

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Applied Mechanics Section
Mechanical Research Department

Several alternative containers are presently being considered for the disposal in a deep underground repository of used fuel bundles from CANDU nuclear power generating stations. The outer shell of the containers will be made of a corrosion resistant metal such as titanium or a metal with low corrosion rate such as copper.

The containers are required to remain leak-tight for at least 500 years of corrosion and structural changes caused by the repository environment. Structural damage may result from excessive plastic strains caused by plastic deformation and creep. As part of a long term assessment program, creep is estimated for three metals (high-purity oxygen-free copper, commercially pure titanium and mild steel) at temperatures between 100 and 150°C. Creep in steel and titanium is estimated using our experimental results. Creep in copper is approximated using the available literature results. Creep strain in steel is lower than in the other two metals. Tests showed that creep starts when stress exceeds 67% yield and increases quickly as the stress approaches yield. It exceeds 1% strain at yield stress after 500 years. Creep strain in titanium is more pronounced. It starts at about 50% yield and the cumulative 500-year creep strain exceeds 1% at a stress level of 85% yield. Creep in copper is high and it should not be ignored at any stress level.

Creep analyses requires time integration over the postulated container life of 500 years. This can be expensive and not always viable. An alternative approach is proposed to eliminate time integration and to simplify the analysis.

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TABLE OF CONTENTS

NOMENCLATURE ii

LIST OF TABLES iii

LIST OF FIGURES iii

1.0 INTRODUCTION 1

2.0 CONTAINER DESIGN 1

3.0 MECHANICAL PROPERTIES OF CONSIDERED METALS 2

4.0 CREEP IN METALS 2
- 4.1 Description of Creep 2
- 4.2 Creep Equations 2
- 4.3 Stress Relaxation 3
- 4.4 Creep Properties of Container Metals 3

5.0 LITERATURE BASED CREEP ESTIMATES 3
- 5.1 Creep in Steel at Low Temperature 3
- 5.2 Creep in Titanium 4
- 5.3 Creep in Copper 4

6.0 OHRD CREEP TEST PROGRAM 4
- 6.1 Test Equipment 4
- 6.2 Creep in Steel 4
- 6.3 Creep in Titanium 4
- 6.4 Creep in Copper 5

7.0 PROPERTIES TO BE USED IN ANALYSIS 5

8.0 TIME INTEGRATION - TEST CASE 6

9.0 CONCLUSIONS 6

10.0 ACKNOWLEDGMENTS 7

REFERENCES 8

DISTRIBUTION ..... last

NOMENCLATURE

A	-	Creep equation coefficient
e	-	Base of natural logarithm
E	-	Young's modulus of elasticity
m	-	Creep time exponent
n	-	Creep stress exponent
r	-	Creep temperature exponent
t	-	Time
T	-	Temperature (°C)
Tm	-	Melting temperature (in K)
ε	-	Strain
ε_c	-	Creep strain
ε_o	-	Initial strain
$\dot{\varepsilon}$	-	Strain rate ($d\varepsilon/dt$)
$d\varepsilon_c/dt$	-	Creep strain rate
σ	-	Stress

LIST OF TABLES

Table I	Physical Properties of Metals
Table II	Coefficients of Creep Equations
Table III	Recommended Time Steps for Creep Analysis
Table IV	Creep In OFHC Copper
Table V	Results of Creep Tests in Titanium
Table VI	Results of Rod Test Case
Table VII	Results of Frame Test Case

LIST OF FIGURES

Figure 1	Schematic Representation of a Creep Rupture Curve
Figure 2	Layout of Selected Containers
Figure 3	Stress-Strain Curves
Figure 4	Estimated Creep Strains
Figure 5	500-Year Creep Strain
Figure 6	Creep Strains for Use in Analysis
Figure 7	500-Year Creep Strain in Steel
Figure 8	Creep Test Rig
Figure 9	Creep Test Results in Steel
Figure 10	500-Year Extrapolated Test Results in Steel
Figure 11	Results of Creep Tests in Titanium
Figure 12	Extrapolated Titanium Creep Test Results
Figure 13	Test Case Finite Element Model
Figure 14	Creep Curve for Test Case Analysis

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LONG-TERM CREEP ASSESSMENT OF CANDIDATE METALS FOR HIGH LEVEL NUCLEAR WASTE DISPOSAL CONTAINERS - INTERIM REPORT

1.0 INTRODUCTION

A program is underway which should facilitate disposal of used fuel bundles removed from CANDU nuclear reactors in durable containers. According to the program, the containers will be disposed of in a deep underground repository. Several alternative containers are being developed. Some of the designs are shown in Figure 1. The outer shell of the containers will be made of a corrosion resistant metal such as titanium or metal with low corrosion rate such as copper. The shell will not be able to support the postulated external pressure of 13 MPa alone. To maintain the shell integrity, it will be internally supported by variety of mediums such as a granular material (eg. glass beads), a cast metal matrix such as lead or by a strong internal cask made of steel or cast iron.

Design of the repository system requires that the containers must not breach due to excessive strains and corrosion for 500 years. Corrosion is considered in the stress analyses because local and general corrosion causes thinning of the container's shell and increases strain in the corroded areas. Strain in a container has three components: elastic, plastic and creep. As part of the long term container assessment program, creep strain is estimated in three metals (mild steel, commercially pure titanium and oxygen free, high purity copper), at a temperature of about 125°C. Creep in steel and titanium is estimated using published data and our experimental results. Creep in copper is estimated using only the limited results available in literature.

This report presents results of the work done since beginning of the program in 1986 until May 1990. The work is still continuing and more data will be obtained. Some results presented here may change as new data becomes available. This report presents only interim results to facilitate progress on the finite element analysis.

2.0 CONTAINER DESIGN

Several alternative container designs are considered in the used fuel bundle disposal program. They are divided into two groups; namely stressed-shell containers and supported-shell containers. Stressed-shell containers have an adequate thickness to support all external loading. In these containers, the shell thickness would be relatively large and it may not be technically and economically viable to make them of corrosion resistive metals. The supported-shell containers have a thin titanium or copper shell supported by an inner structure. Several supporting structures are considered:

- granular material (particulate) packed into all void spaces/2/
- cast metal matrix/3/
- steel or cast iron cask overpacked by a corrosion resistive shell/4/.

3.0 MECHANICAL PROPERTIES OF CONSIDERED METALS

Physical properties of mild steel, commercially pure Grade 2, B265 titanium and Oxygen-Free, High-Conductivity (OFHC) copper are listed in Table I. Properties of titanium and copper are obtained from references /5 and 6/ respectively.

A typical stress-strain curve for OFHC copper at 150°C is shown in Figure 2. The curve shows a small elastic zone. Yield of 0.2% permanent deformation occurs at about 55 MPa (8 ksi). Young's modulus of elasticity is 113,000 MPa (16,400 ksi). The plastic region is large. A two-inch specimen is expected to fail at above 60% strain and at a stress of 115 MPa (16.5 ksi) (see Table I).

4.0 CREEP IN METALS

4.1 Description of Creep

Creep is a property of metal involving time-dependent deformation. The rate of creep depends on both temperature and stress level. High-temperature creep deformation is usually divided into three consecutive stages, shown in Figure 3:

- Primary creep starts as soon as temperature and load are applied and is characterized by creep rates that decrease with time.
- Secondary creep has a constant creep rate.
- In tertiary creep, the creep rate increases with time until rupture. This stage can only occur under tensile loading.

The three stages of creep may exist in metals at temperatures above 0.3 Tm (where Tm is the melting temperature in degrees Kelvin or Rankin). Secondary creep is not anticipated below 0.3 Tm. The tertiary creep may occur at low temperatures under tensile stress near yield/1/.

4.2 Creep Equations

The three stages of creep are frequently described by a creep rate equation:

$$d\varepsilon/dt = A\,\sigma^n e^{-rT} t^m \qquad (1)$$

Coefficients m, n, r and A are independent of time. Coefficient m is equal to zero for uniform, secondary creep. For primary (decreasing with time) creep, the coefficient m is less than 0 and reaches its least value of minus one for logarithmic creep. For tertiary creep, m is greater than 0. F. Garofalo /1/ proposes that for face-centered cubic and body-centered cubic materials at temperatures between 5% and 30% of melting temperature, creep strain varies linearly with the logarithm of time:

$$\varepsilon = A' \ln t + \varepsilon_o \qquad (2)$$

Results of our tests have shown that at stresses below 90% yield, equation 2 is valid for both steel and titanium. As stresses approach yield, an exponential equation with m between -1 and 0 was found to be more applicable.

The above equations are approximate. When data obtained from literature /9/ for mild steel at 400°C was fitted into equation 1, values of coefficients varied widely. For example, values for m ranged from -0.055

to -0.5. The creep temperature exponent varied from 0.04 to 0.06. The creep stress exponent n was nearly constant at 7. Results of the test program gave more consistent values, as described in Section 6 below.

4.3 Stress Relaxation

If creep deformation is not load-controlled, stress relaxation can result. The largest creep deformations occur in the highest stressed areas and result in redistribution of stresses over a larger area. Creep can be expected to continue in highly stressed locations until stresses drop below a creep threshold value (approximately 67% yield in steel or approximately 50% yield in titanium).

4.4 Creep Properties of Container Metals

In the repository, the container shell will be at a temperature of about 100°C and under an external pressure of up to 13 MPa. Under these conditions, creep strains are anticipated and they can become large as stresses approach yield. Our tests show that the logarithmic equation (equation 2) fits experimental results well for steel and titanium at stresses below 90% yield. The exponential equations should be used for stress levels over 90% yield. The exponential equation is appropriate for copper at all stress levels. Coefficients of the equations are listed in Table II, for the three metals as obtained from our test program. The equations are plotted in Figure 4, for different container ages. From the graphs, we can see that for steel and titanium, creep diminishes significantly with time and remains nearly constant after 100 years. Although yield and ultimate strengths are nearly the same for the two metals, creep strength of titanium is much lower. As anticipated, the resistance of copper to creep is the lowest. Creep strain in copper is high and strain rate can be significant even after 500 years. Results extrapolated to 500 years are shown in Figure 5.

All creep tests were conducted at temperatures between 100 and 150°C.

5.0 LITERATURE BASED CREEP ESTIMATES

5.1 Creep in Steel at Low Temperature

Creep in steel is described in literature /9,10/ for temperatures above 350°C (or 37.6% Tm) while the IBSS container will operate at about 100°C (373 K or 22.5% of melting temperature Tm). Two literature sources were used in the analysis /9 and 10/, presenting results of up to 10,000-hour tests (1.14 years).

The literature results were extrapolated to 500 years. Stress levels considered in the literature are relatively low (below 120 MPa). They were extrapolated to 225 MPa. The third extrapolation was used to estimate the creep properties of steel at the postulated cask temperature of 100°C. Such multiple extrapolation is likely to cause inaccuracies. A detailed discussion of the extrapolation method and results are included in reference /4/. Results of the triple extrapolation are shown in Figure 7.

The line in Figure 7 suggests that there may be a threshold stress in steel below which creep will not occur. A stress of 130 MPa is assumed to be this value (for 125°C) since we could not measure creep rate at this stress in the subsequent test program. The creep strain data from Figure 7 can be used to estimate the creep rate coefficients in the logarithmic creep strain equation.

$$\varepsilon = A\,\sigma^{n} \ln (t) + \varepsilon_{o} \qquad (3)$$

Value ε_{o} represents the initial, pre-creep strain. The remaining equation coefficients are estimated as:

$$A = 2.0\times10^{-20},\ n = 7.0$$

Confirmation of the above results was obtained from our test program.

5.2 Creep in Titanium

A literature search was conducted but the published results could not be extrapolated satisfactorily. Analysis of the scattered literature data was abandoned in favor of a test program (currently underway).

5.3 Creep in Copper

Literature study of creep in copper produced only a limited amount of data. Since creep tests on copper are delayed, the available data will be used to initiate the finite element analysis. Reference /6/ gives four points (see Table IV) that can be used to calculate coefficients of the exponential creep equation (see Table II). The equation is approximate and tests are required to either verify or modify it.

6.0 OHRD CREEP TEST PROGRAM

6.1 Test Equipment

To gain better confidence in the results obtained from literature, a uniaxial test program was conducted on 1/4-inch diameter rods of the material to be evaluated. The rods were 10-feet long to obtain more accurate measurements of small changes in strain. The deformations were measured using two types of instruments: LVDT's and dial gauges. The layout of the test station is shown in Figure 8.

ASTM recommends the use of 2-inch specimens for testing of creep properties in metals. Our tests did not comply with this recommendation. However, we feel that our tests are still representative of the material behavior as they provided averaged creep data over the extended length of the specimen. Rods used in the tests were marked every two inches before testing. Following each test, the two-inch spaces were inspected to ensure that localized elongation did not occur. Tests on the rods were conducted using constant load rather than constant stress condition. Although constant stress would have been more desirable, the error was below 1%, in all tests.

6.2 Creep in Steel

Five tests were conducted using steel rods. Results of the tests are shown in Figure 9. An initial (first hour) deformation is not shown in this figure to eliminate the initial, elastic deformation. Coefficients of equations for each test are shown in Table II. At tensile stress below 70% yield, the 500-year creep strain is negligibly small. It increases rapidly with increased stress. Logarithmic creep was obtained for stresses below 90% yield. As the axial stress was increased to near yield (tests at 95 and 100% yield in Figure 9), the deviation from the logarithmic curve became apparent and an exponential relationship became more accurate (see Figure 9 and Table II). The results from the tests were extrapolated to 500 years and superimposed on the curve for steel in Figure 7 and shown in Figure 10.

6.3 Creep in Titanium

The same 10-foot long rig shown in Figure 8 was used to test the titanium rods. Creep tests on titanium rods have been continuing since December, 1987. Four tests have now been completed. They ranged from 1,368 to 6,386 hours. The tests were run at stress levels of 50%, 67%, 75% and 80% yield for titanium at 125°C. Strains were recorded every 24 hours starting 60 minutes after the rods were loaded, to eliminate the initial strain (ε_o). Results of the tests (shown in Figure 11) were used to obtain exponential and logarithmic creep strain equations.

The least root square technique is the most common method for calculating equation coefficients from experimental data. This curve fitting technique was used for both logarithmic and exponential equations. The results of the least root square extrapolation are shown in Table V. Large discrepancy exists between

the 500-year strains calculated from the two equations. Based on the average strain variation between the linearized values and test results, logarithmic extrapolation should be more accurate.

As an alternative to the least root square method, creep strains at selected times were substituted directly into the logarithmic and exponential equations to calculate the equation coefficients. Creep strains at many time intervals during the test were used for the substitutions. Many equations were obtained for time intervals from 200 hours to the full test duration. From the equations, 500-year creep strain was estimated and plotted in Figure 12. Using logarithmic equation, the calculated 500-year creep strain from the first 200 hours of a test was nearly the same as that calculated from the full length 6,300-hour test (for all four specimens). From the exponential equation, the estimates were very high for a short test. They appear to converge to the results of the logarithmic extrapolation as the tests continued (see Figure 12). Creep in titanium at stresses up to 80% yield is assumed to follow the logarithmic law (see Table II).

It was determined that creep in titanium can be represented by a logarithmic equation. Since titanium has a body-centre-cubic structure and the container temperature of 373 K is below 0.3 of melting temperature of 2,073 K, the logarithmic assumption should be reasonable (see reference /1/). As yield is approached, the deformation and creep strain would be higher than estimated by the equation, and the resulting stress would be lower. More tests are required to better assess the effect of yield point on creep.

6.4 Creep in Copper

Plans to conduct an extensive test program on creep in copper at 100 to 125°C are underway. The tests will start in 1991.

7.0 PROPERTIES TO BE USED IN ANALYSIS

The finite element analysis, currently underway, includes the effect of creep. Because creep is time dependent, its analytical simulation must involve time integration of a creep strain rate equation over the 500-year postulated container life. If the integration is performed by a computer, it may require large computer resources and many incremental time steps. Large errors may also be involved. Time integration cannot be performed using the ABAQUS code for values of m near -1. ABAQUS assumes that creep is described by a creep strain rate equation in form

$$\dot{\varepsilon} = A\, S^n\, t^m$$

This equation is integrated by the program to a form

$$\varepsilon = A\, S^n\, t^{m+1}/(m+1)$$

From the equation for the creep strain rate, it appears that if the first hour of creep is omitted in the analysis, time integration should converge. This is not true in ABAQUS where the value for m cannot equal -1. If t in the last equation represents an initial time increment used in a numerical analysis, ε represents a strain increment in a single iteration. Even if we approximate m by -0.999, strain will change by 1,601.4% in steel and by 75,262.8% in titanium, at 200 MPa stress (as calculated from the last equation). This result is independent of time step and is unrealistically high.

Creep integration used in finite element analysis may have very small time steps, not suitable for the required long term analyses. Table III lists the recommended time steps for creep analysis, based on the method postulated in references /7 and 8/.

An alternative to the long term integration has been proposed and shown to be adequate (see section 8.0). Stress-strain curves used for elastic-plastic analyses were modified by adding 500-year creep strain and elastic-plastic strain to form new curves (see Figure 4). The curves were then linearized for input to the finite element analysis (see Figure 6). The simplified analysis incorporates the effect of creep, plasticity and elasticity.

8.0 TIME INTEGRATION - TEST CASE

Two test cases are used to illustrate the validity of the simplified creep analysis. The analysis is conducted using time integration over one month (720 hours). Since we could not use the logarithmic equation in the integration, it was substituted by two arbitrarily selected exponential equations with coefficient m equal to -0.85 and -0.50. The selected exponential strain equations are compared with the logarithmic equation in Figure 14 and show reasonable agreement. The equations are only valid for the 30-day test cases and cannot be used for any other extrapolation. Results of time integration runs were compared with results of an elastic-plastic runs in which strains were a sum of elastic, plastic and creep components.

Two simple finite element models were built which consisted of:

- a 3.0 m long straight rod simulating the tested rods. The rod was loaded to 80% yield for comparison with the test result.

- a frame modeled with 8 shell elements (see Figure 13). The model was cantilevered at the base. Load of 30 N was applied at the free end. The shell elements had properties of titanium, including plasticity. Shell elements were used in the test case because container shell is most frequently modeled using this type of element.

Results for the rod analyses are shown in Table VI. Good correlation was obtained between test results and the time integration method. The simulated elastic plastic analysis (using ABAQUS) produced conservative results with about 30% difference.

Results of the elastic-plastic analysis of the frame are shown in Table VIIa and b, for the two exponents. They show that 25% of the final creep induced deformation was obtained in the first 7 hours and over 50% in the first 100 hours. Lower exponent (-0.85) resulted in faster convergence. Similar time stepping was used in the simplified elastic-plastic run. Convergence was much faster here. In the first 7 hours of the run, 80% of the final creep induced deformation was obtained (see Table VIIc).

The results from the two runs are compared in Table VIId. Deformations and strains are up to 36% lower in the run using time integration and the stress is 11% lower. The large difference is due to different stress-strain curves used in the two runs. Integration run required 275 iterations with an error of about 1% per iteration. Results from both runs contain errors. Results from the simplified run are more conservative.

9.0 CONCLUSIONS

A test program to investigate the creep strain in steel, titanium and copper is in its early stages. However, creep equations for the three metals were formulated using results of our tests and published data. The presented equations might be modified in the future, as more results become available. The presented results are adequate for the finite element analysis, considering the errors involved in the 500-year extrapolation of test results, simplifications used in analysis and error anticipated from complex, non-linear finite element analysis.

A simplified method for performing elastic-plastic analysis including creep has been developed and shown to be adequate.

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TABLE I

PROPERTIES OF METALS

Property	Unit	Steel[1]	Titanium[2]	Copper[3]
Density	g/cm^3	7.85	4.48	8.9
Yield Strength	MPa	250	216	55
Ultimate Strength	MPa	425	345	115
Modulus of Elasticity	MPa	200,000	100,000	113,000
Strain to Failure	%	25	50	60
Melting Temp.	°C	1370	1820	1083
Thermal Conduction	W/m°C	68.9	15.2	397
Thermal Expansion	1/°C	12.4 E-6	8.55 E-6	18 E-6
Specific Heat	J/g°C	0.13	0.54	0.39

Notes:

[1] AISI C1020

[2] Commercially Pure Titanium B265, Grade 2

[3] Oxygen-free High-conductivity Copper

TABLE II

COEFFICIENTS OF CREEP EQUATIONS

Metal	Stress Level (% Yield)	A	n	B	m	n
Steel	0 to 90	1.04×10^{-18}	6.60	--	--	--
Steel	90 up	--	--	1.85×10^{-69}	0.22	27.846
Titanium	0 to 90	3.54×10^{-13}	4.94	--	--	--
Copper	All	--	--	1.0×10^{-7}	0.35	2.8

The creep test results are approximated by equations

$$\varepsilon = A\sigma^n \ln t \quad \text{or} \quad \varepsilon = B\sigma^n t^m$$

(stress σ expressed in MPa, time in hours and strain in %)

Creep tests were conducted at 100 to 150°C

TABLE III

RECOMMENDED TIME STEPS FOR CREEP ANALYSIS

Metal	E (MPa)	A	n	σ	ΔT (hr)
Steel	200,000	1.04×10^{-18}	6.60	200	0.126
Titanium	100,000	3.54×10^{-13}	4.94	200	0.007
Copper	113,000	1.0×10^{-7}	2.80	80	0.016

Time Step Equation $\Delta T = 1.33/(EAn\ \sigma^{(n-1)})$(hr)

TABLE IV

CREEP DATA FOR OFHC COPPER

Time (hr)	Stress (MPa)	Creep Strain (%)
1000	69	0.001
1000	124	0.010
1000	145	0.100
1000	186	1.00

TABLE V

RESULTS OF CREEP TESTS ON TITANIUM

Extrapolation		500-year Creep Strain (%) at Stress				Variation (1) x 10
Technique	Type	80% Yield	75% Yield	67% Yield	50% Yield	
Least Root Sq.	Logarithmic	0.754	0.412	0.203	0.083	86.4
	Exponential	453.9	11.306	1.007	0.408	1266.0
Substitution	Logarithmic	0.812	0.484	0.225	0.087	
	Exponential	5.428	0.630	0.439	0.261	

(1) Largest average variation between the interpolated curve and measured test results in the least root square method.

TABLE VI

RESULTS OF ROD TEST CASE

	Exponent m	Deflection (mm)	Stress (MPa)	Strain (%)
Elastic - Plastic		-11.38	173.5	0.379
Creep	-0.85	-9.96	173.4	0.331
Creep	-0.50	-9.96	173.4	0.331
Measured		-9.32	172.8	0.311

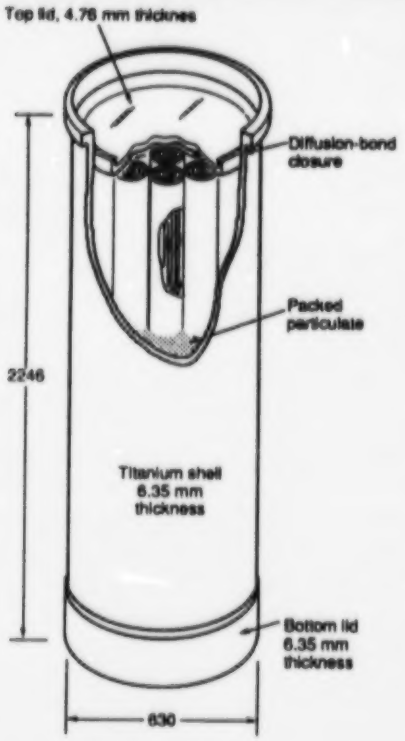
Parameters

Material: Titanium
Load: 80% Yield
Time Duration: 720 hours

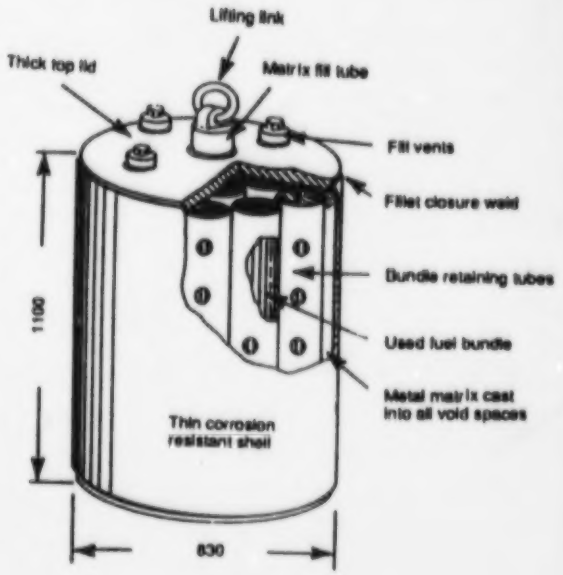
TABLE VII

RESULTS OF FRAME TEST CASE

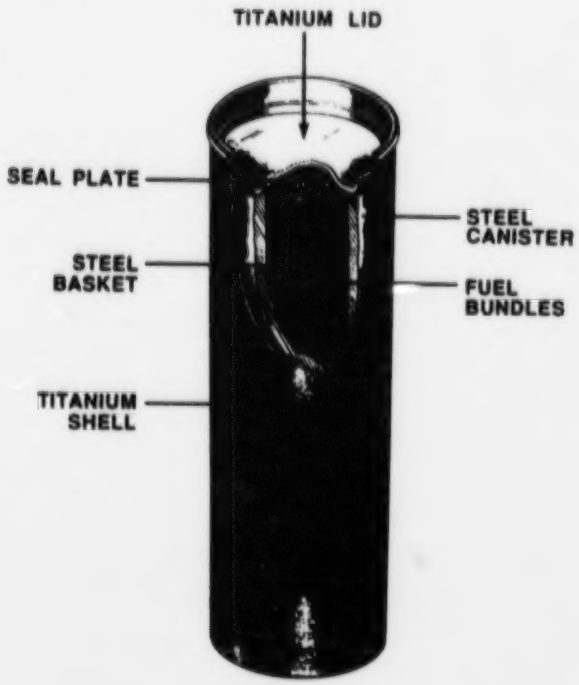
Exponent m	Run	Time (hr)	Displacement (mm)		Stress (MPa)	Strain (%)
			X	Z		
(a) EFFECT OF TIME INTEGRATION						
-0.85	Time Integration	0.0	1.47	-3.90	187.0	0.187
		2.3	1.70	-4.40	159.2	0.213
		30.0	1.77	-4.54	153.2	0.225
		121.6	1.81	-4.63	149.9	0.231
		243.8	1.83	-4.67	148.3	0.233
		549.4	1.85	-4.73	146.5	0.237
		720.0	1.86	-4.75	146.0	0.238
(b) EFFECT OF TIME INTEGRATION						
-0.50	Time Integration	0.0	1.47	-3.90	187.0	0.187
		2.4	1.53	-4.01	180.0	0.194
		41.5	1.64	-4.25	166.5	0.208
		124.9	1.71	-4.41	158.6	0.218
		249.9	1.76	-4.53	153.4	0.225
		541.7	1.84	-4.69	147.6	0.235
		720.0	1.87	-4.76	145.6	0.239
(c) EFFECT OF SIMULATED CREEP						
	Log Simulation	0.0	1.47	-3.90	187.0	0.187
		2.4	2.45	-6.41	183.8	0.311
		41.5	2.56	-6.63	174.2	0.326
		124.9	2.62	-6.74	169.2	0.334
		249.9	2.65	-6.81	166.8	0.338
		541.7	2.68	-6.87	164.0	0.343
		720.0	2.70	-6.90	162.6	0.345
(d) COMPARISON OF RESULTS						
-0.85	Time Step	720.0	1.86	-4.75	146.0	0.238
-0.50	Time Step	720.0	1.87	-4.76	145.6	0.239
	Log Simulation	720.0	2.70	-6.90	162.6	0.345
	% Differ.		36.3	36.7	11.0	36.3



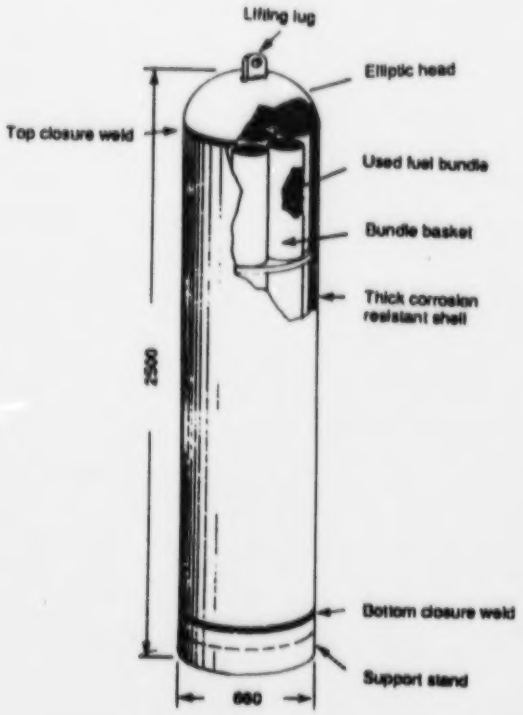
a) TWPP Container



b) Lead Matrix Container



c) IBSS Container



d) Stressed Shell Container

FIGURE 1

ALTERNATIVE CONTAINER DESIGNS

90-241-K
183534-G25-RD

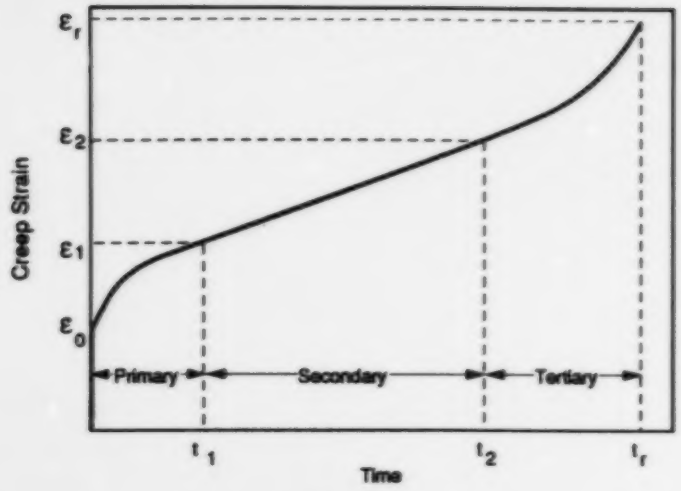
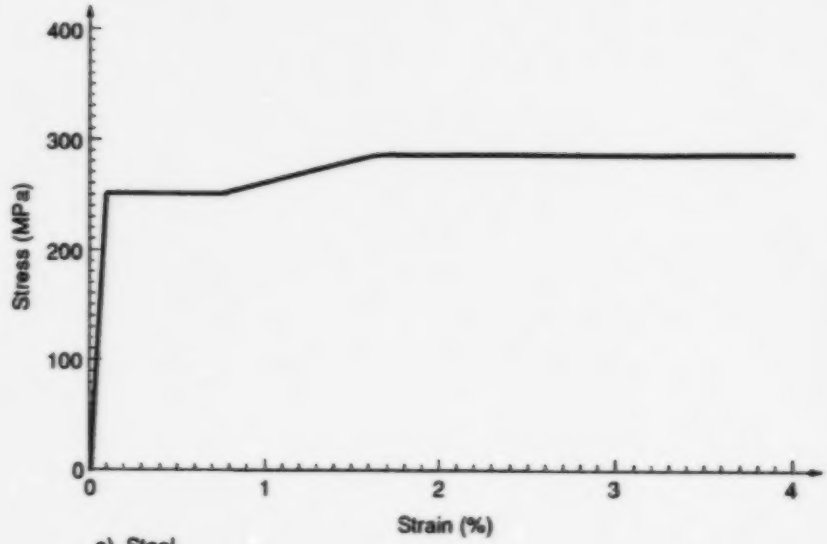
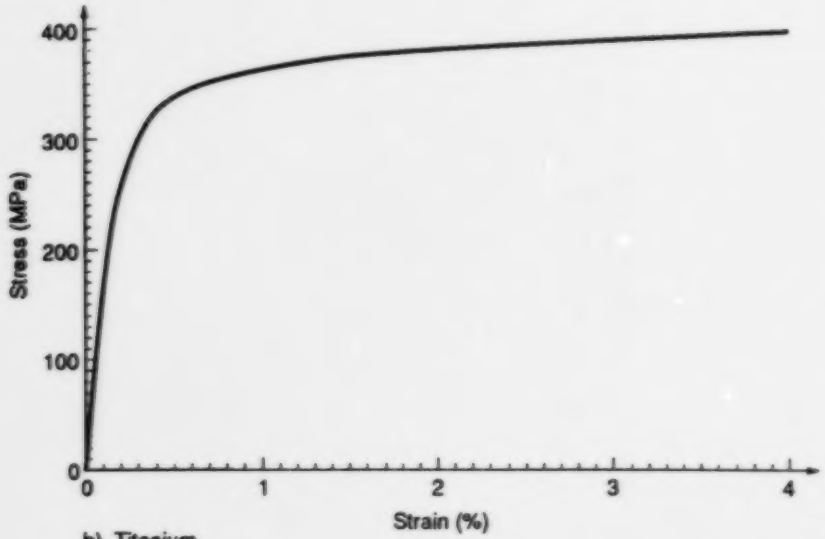


FIGURE 3

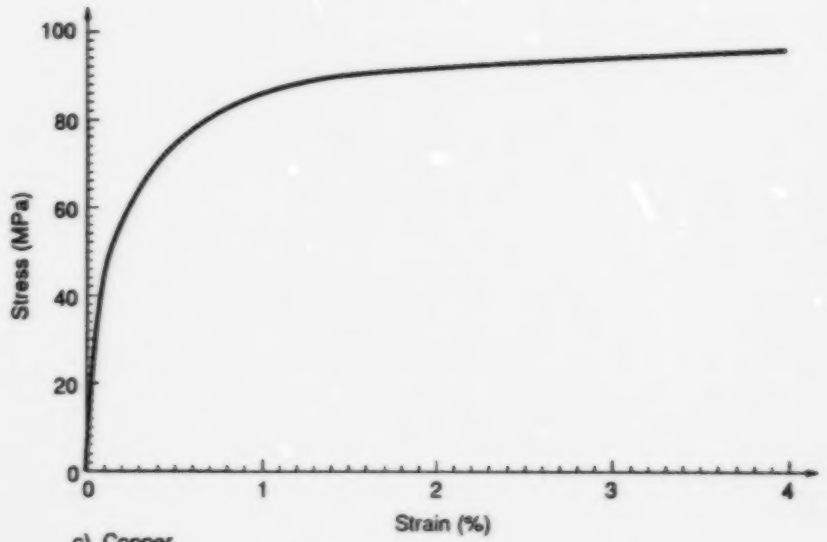
SCHEMATIC REPRESENTATION OF A CREEP- RUPTURE CURVE



a) Steel



b) Titanium



c) Copper

FIGURE 2

STRESS-STRAIN CURVES

90-241-K
18348Z-G25-RD

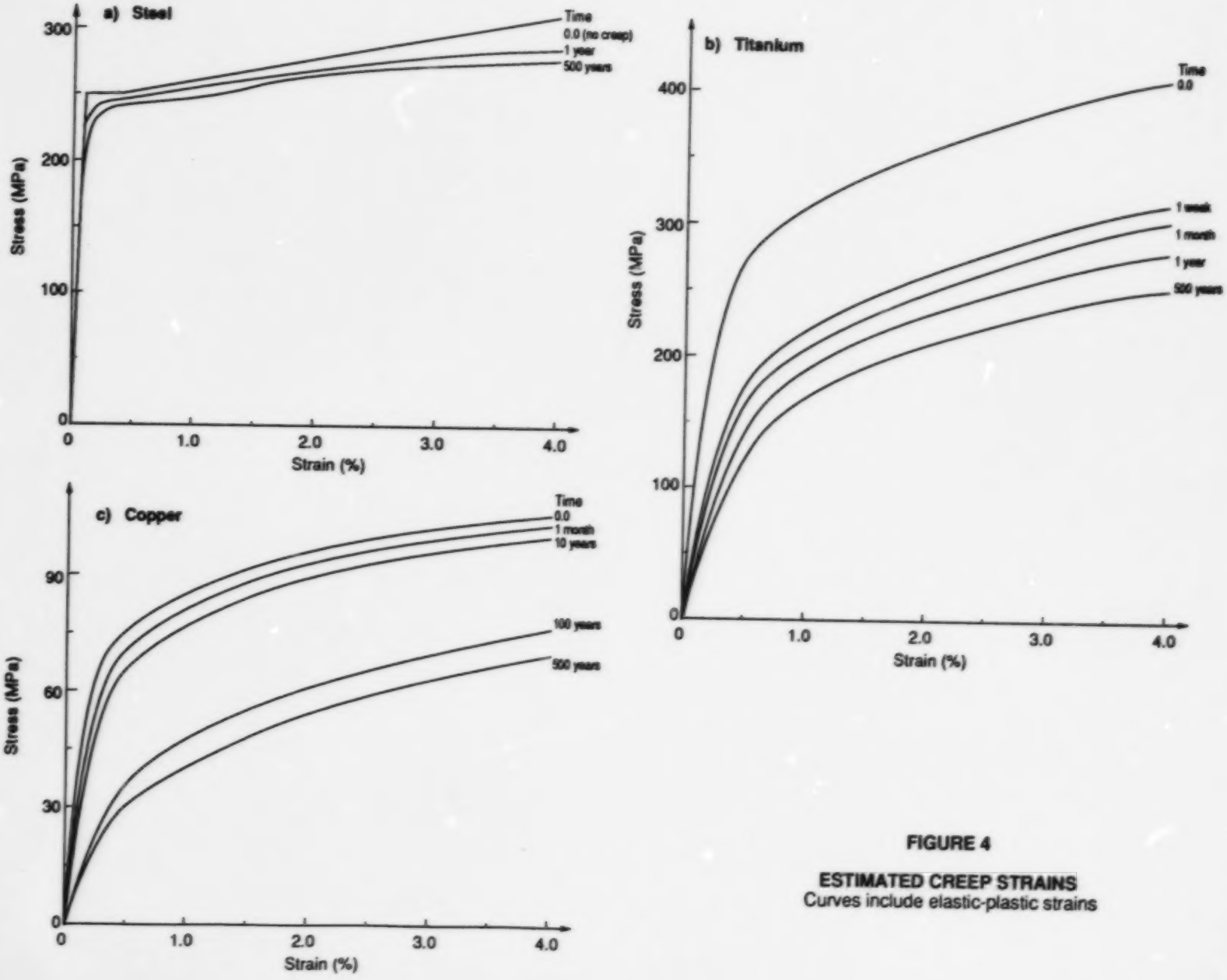


FIGURE 4

ESTIMATED CREEP STRAINS
Curves include elastic-plastic strains

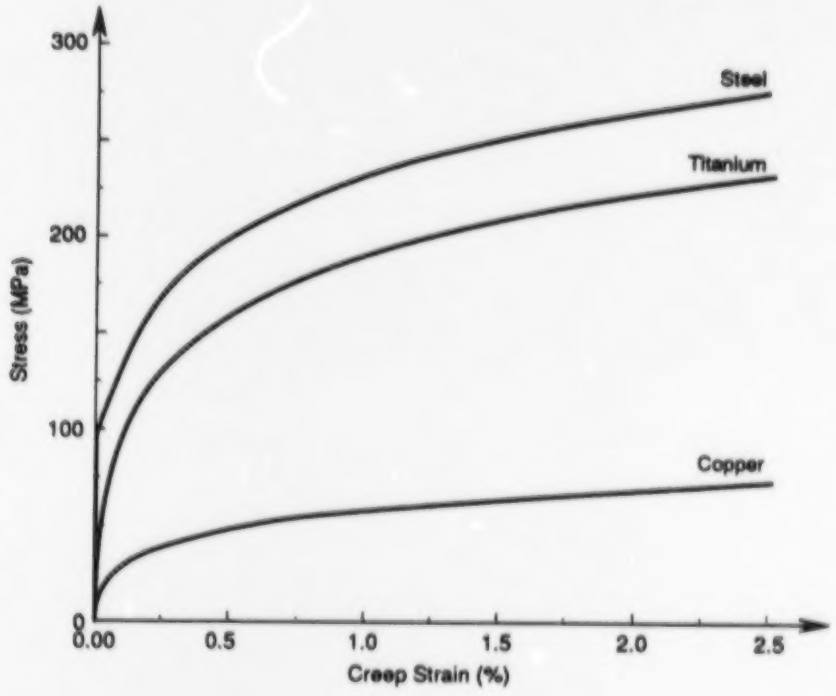


FIGURE 5

500-YEAR CREEP STRAIN

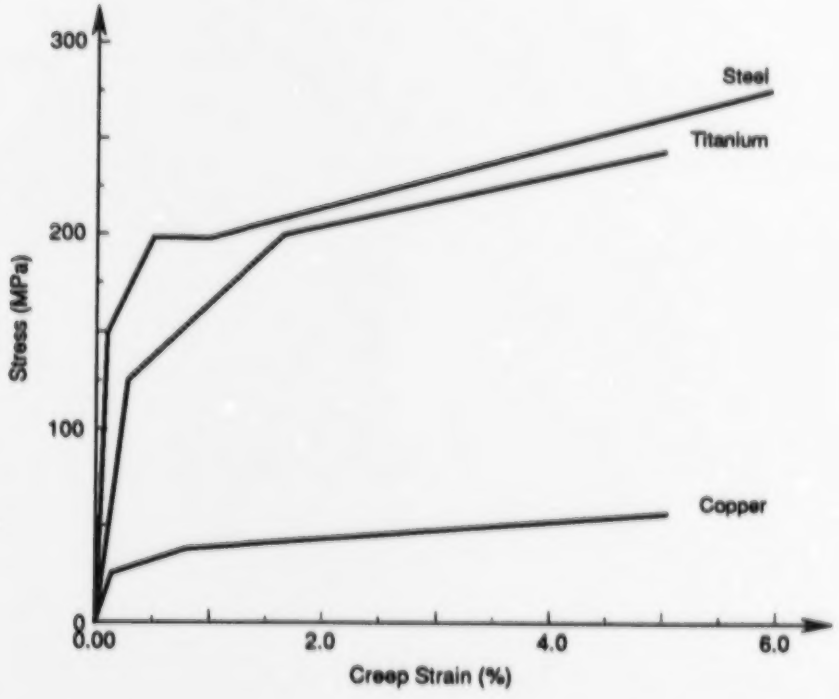


FIGURE 6

STRAIN CURVES FOR USE IN ANALYSIS WITH 500-YEAR CREEP STRAIN

90-241-K
183497-G25-RD

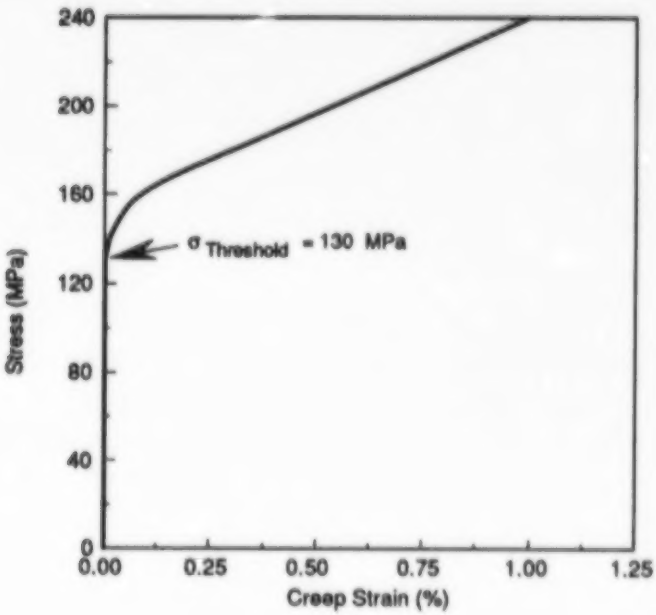


FIGURE 7

500-YEAR CREEP STRAIN IN STEEL
(Temp. = 125 °C)

FIGURE 8

CREEP TEST RIG

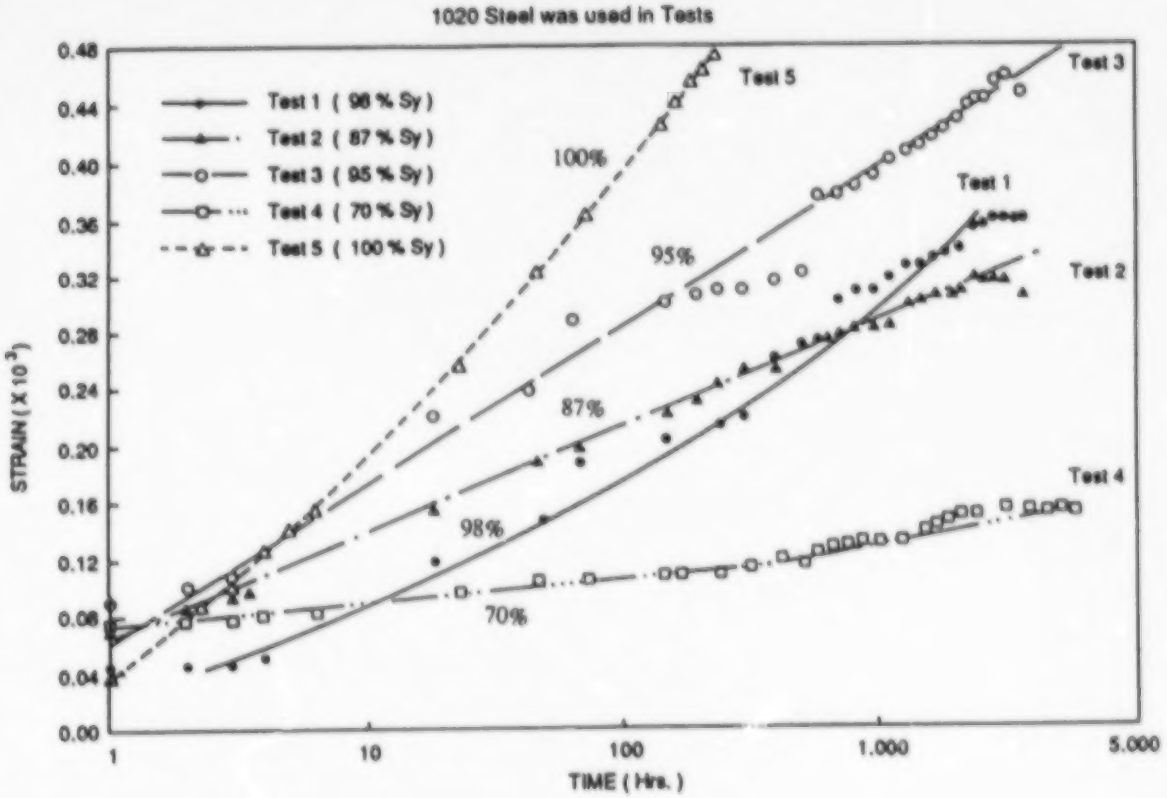


FIGURE 9

CREEP TEST RESULTS IN STEEL (T = 125 °C)

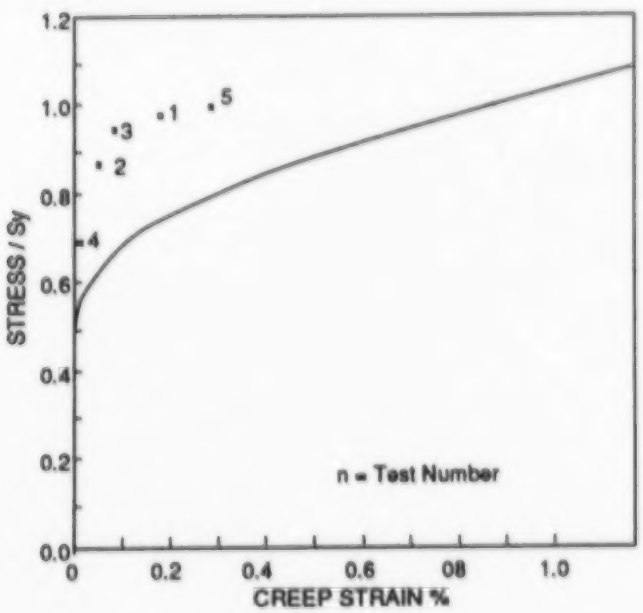


FIGURE 10

500- YEAR EXTRAPOLATED TEST RESULTS

90-241-K

193526-G25-RD

FIGURE 11

RESULTS OF CREEP TESTS IN TITANIUM

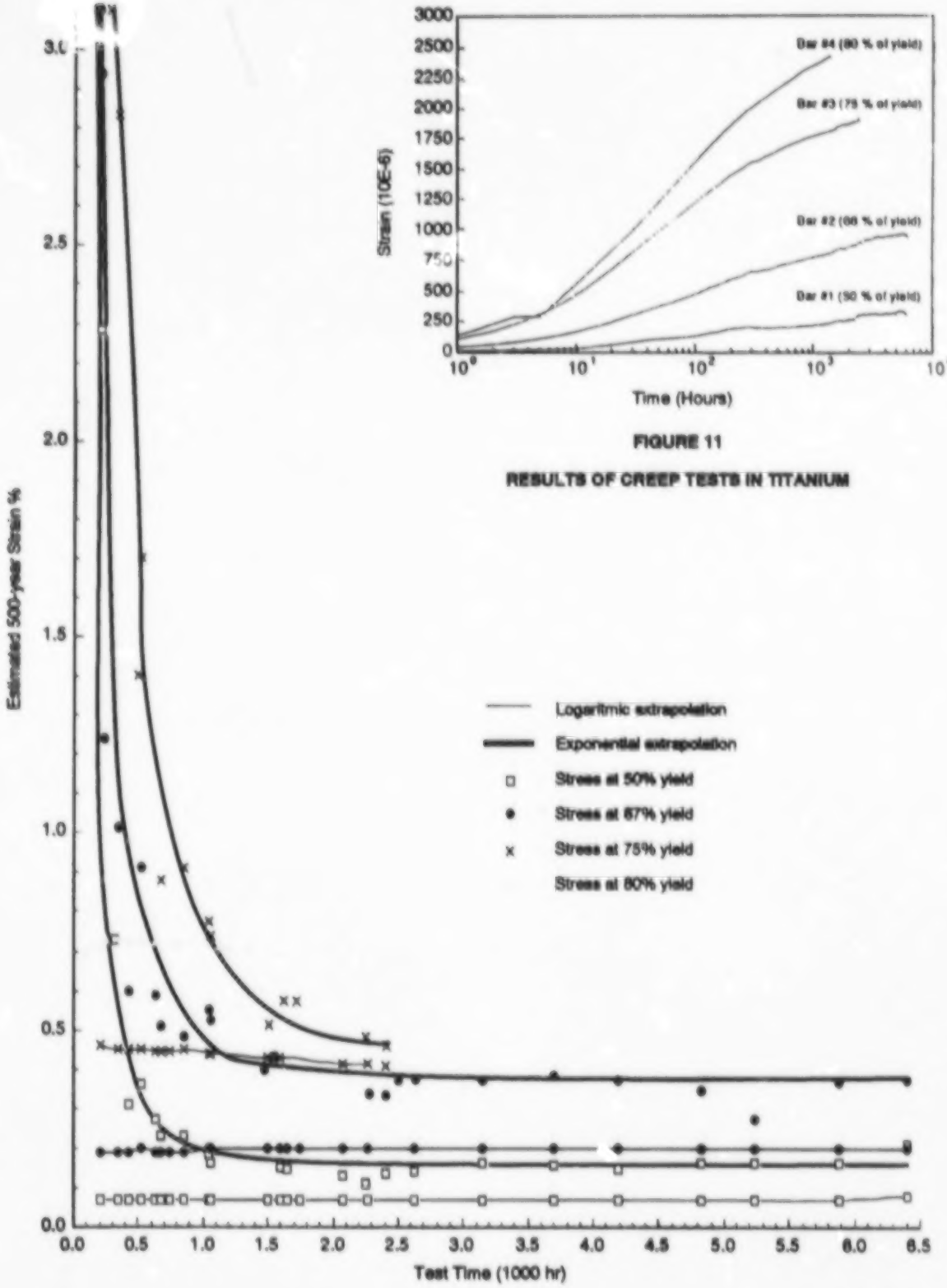


FIGURE 12

EXTRAPOLATION OF TEST RESULTS

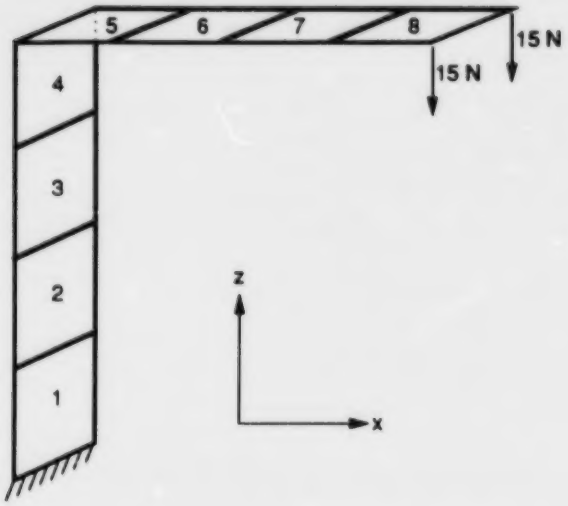


FIGURE 13

RESULTS OF CREEP TESTS IN TITANIUM

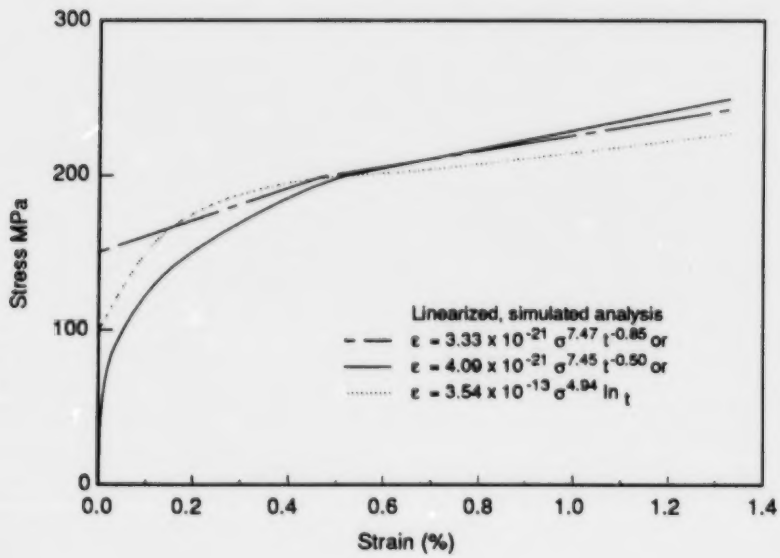


FIGURE 14

CREEP CURVES FOR TEST CASE ANALYSIS